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Observations of pre-stellar cores

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Abstract. Our understanding of the physical and chemical structure of pre-stellar cores, the simplest star-forming sites, has significantly improved since the last IAU Symposium on Astrochemistry (South Korea, 1999). Research done over these years has revealed that major molecular species like CO and CS systematically deplete onto dust grains at the interior of pre-stellar cores, while species like N_2H^+ and NH_3 survive in the gas phase and can usually be detected towards the core centers. Such a selective behaviour of molecular species gives rise to a differentiated (onion-like) chemical composition, and manifests itself in molecular maps as a dichotomy between centrally peaked and ring-shaped distributions. From the point of view of star-formation studies, the identification of molecular inhomogeneities in cores helps to resolve past discrepancies between observations made using different tracers, and brings the possibility of self-consistent modelling of the core internal structure. Here I present recent work on determining the physical and chemical structure of two pre-stellar cores, L1498 and L1517B, using observations in a large number of molecules and Monte Carlo radiative transfer analysis. These two cores are typical examples of the pre-stellar core population, and their chemical composition is characterized by the presence of large freeze out holes in most molecular species. In contrast with these chemically processed objects, a new population of chemically young cores has started to emerge. The characteristics of its most extreme representative, L1521E, are briefly reviewed.

Keywords. astrochemistry, molecular processes, radiative transfer, stars: formation, ISM: clouds, ISM: molecules, radio lines: ISM

1. Pre-stellar cores as star-forming sites

Pre-stellar (or starless) cores are the simplest star-forming sites. They are isolated, lie nearby, and form one star (or one binary) at the time; they closely resemble the theorist's ideal of a star forming region. When observed in a molecular tracer like ammonia, a pre-stellar core appears as a centrally concentrated structure containing one or a few solar masses of material and having a typical size of about 0.1 pc (see Figure 1 and Benson & Myers 1989 for further global properties of cores).

Pre-stellar cores are the dominant star-forming sites in nearby molecular clouds like Taurus-Auriga, where stars like our Sun are currently forming in the so-called "isolated mode" (e.g., Shu, Adams, & Lizano 1987). They are not, however, the dominant star-forming regions of our galaxy, as most stars in the Milky Way have formed in groups (e.g., Adams & Myers 2001), and therefore must result from the collapse of more complex gas structures. Still, star formation in isolated pre-stellar cores seems to involve most of the physical elements that we associate with the birth of a typical low-mass star, like gravitational infall, disk formation, and bipolar outflow ejection. All these elements, in fact, were first identified in stars forming in isolated cores, and they can be studied with great detail in these simple environments.

The above reasons of simplicity make pre-stellar cores ideal sites to study the initial conditions of star-formation (e.g., Ward-Thompson et al. 1999). Cores are also the most promising places to test the different competing models of star formation, in particular the (fast) turbulence driven scenario (Mac Low & Klessen 2004) and the (slow)

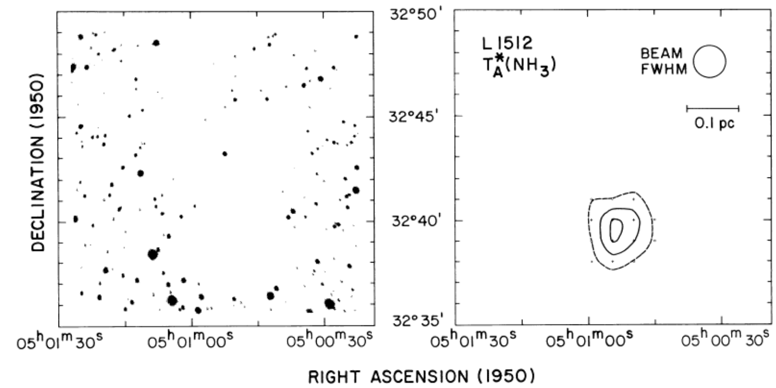

Figure 1. A representative pre-stellar core, L1512. Left: optical image from the Palomar Sky Survey, where L1512 appears as a patch of obscuration against the background of stars. Right: map of the NH_3 emission toward the same region showing L1512 as a centrally concentrated (slightly resolved) object. Figure from Benson & Myers (1989).

magnetically-mediated star formation models (Shu et al. 1987, Mouschovias & Ciolek 1999). By determining how pre-stellar cores contract out of the more diffuse ambient cloud and by what mechanism cores lose their gravitational support and start collapsing to form a star, we may be able to observationally distinguish between these two models.

2. Cores as laboratories of ISM chemistry

Pre-stellar cores are also some of the simplest chemical laboratories in the interstellar medium (ISM) because of their isolation, simple (close to spherical) geometry, and low (10 K), close to constant gas temperature. Despite this simplicity, however, pre-stellar cores are not chemically homogeneous, and the ignorance of this fact has caused in the past serious difficulties when attempting to derive the core internal structure from observations. Early warnings of chemical inhomogeneities were the striking discrepancies found when mapping cores using different molecular tracers. A classical example of this problem are the observations made using NH_3 and CS, two molecular species expected to trace similar gas conditions. As found by Zhou et al. (1989), maps made in NH_3 and CS present systematically different sizes (NH_3 maps are a factor of 2 smaller), different shapes, and often different peak positions. Resolution effects or radiative transfer complexities were soon found insufficient to explain these discrepancies.

A hint of a solution to the tracer discrepancies comes from the recent realization that species like CO and CS are systematically depleted at the centers of cores due to freeze out onto cold dust grains (Kuiper et al. 1996, Willacy et al. 1998, Kramer et al. 1999, Caselli et al. 1999). The identification of molecular freeze out in cores (long expected from theoretical grounds, see Watson & Salpeter 1972) has renewed the interest in the study of dense core chemistry, and it brings promise of resolving the old tracer discrepancies with relatively simple chemical processes. From the point of view of star-formation studies, the identification of freeze out in some molecules is forcing a re-evaluation of the behaviour of the different dense gas tracers under typical core conditions, as we depend on them to infer basic core properties like gas temperature and kinematics. Determining the chemical structure of cores has therefore become a necessary step in our attempt to understand how stars are born.

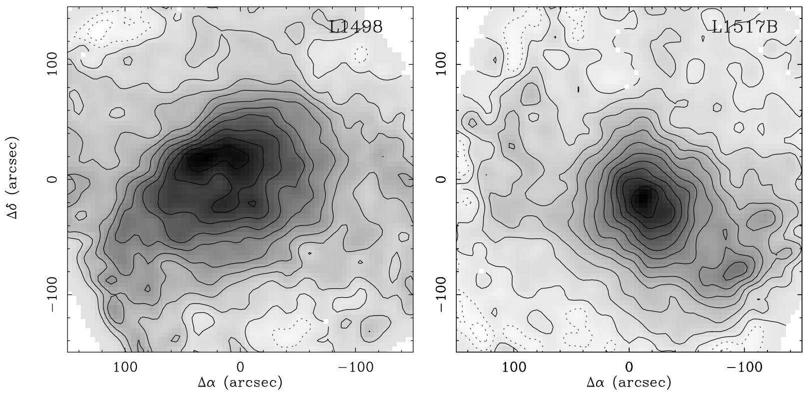

Figure 2. 1.2mm continuum maps of L1498 (left) and L1517B (right). Note the central concentration and close-to-round shape of the emission. First contour and contour spacing are 2 mJy/11″-beam.

3. A molecular survey of L1498 and L1517B

To understand the chemical behaviour of dense gas tracers in star-forming regions, we have carried out a systematic molecular survey of two pre-stellar cores in the Taurus-Auriga cloud complex, L1498 and L1517B (Tafalla, Myers, Caselli, & Walmsley 2004; Tafalla et al. 2005 in preparation). We selected these two cores (Fig. 2) for being isolated, close to round, and otherwise typical cores of their surrounding cloud, and we have observed them in the 1.2 mm continuum and in a large number of molecular lines from 13 different species using the IRAM 30m, Effelsberg 100m, and FCRAO 14m radio telescopes.

The goal of this project is to model self-consistently all the observed emission in order to determine how the different species trace the core interior, and to provide a high quality set of molecular abundances for testing chemical models. We can divide the analysis of the observations in two steps. First, we determine the physical parameters of the cores by modelling their distributions of density, temperature, and gas kinematics assuming that the cores are spherically symmetric. Once these parameters have been fixed, the cores can be seen as laboratories of known physical properties, and the abundances of the different molecular species can be derived directly by fitting their observed emission.

3.1. *Physical structure of L1498 and L1517B*

To derive the density profiles of L1498 and L1517B we rely on the dust continuum emission, as this is the most unbiassed tracer of the core column density. We assume a 1.2mm dust emissivity of 0.005 cm^2 g^{-1} and a dust temperature of 10 K, and we note that these parameters are the largest source of uncertainty of the whole analysis (see Tafalla et al. 2004 for further details). By fitting the radial profiles of 1.2mm continuum emission, we find density profiles very close to those expected for isothermal spheres with central densities of 10^5 and 2×10^5 cm^{-3} for L1498 and L1517B, respectively (see Alves et al. 2001 and Evans et al. 2001 for similar fits to other pre-stellar cores).

To derive the gas temperature profile, we use the NH_3 emission, that we will see below traces well the inner core. From the combined analysis of the emission from the metastable J,K=1,1 and 2,2 levels, we derive constant temperature profiles for both cores with values close to 10 K.

Finally, we derive core turbulent profiles using the linewidth of NH_3(1,1) complemented with other species. We subtract the (constant) thermal component and find an also

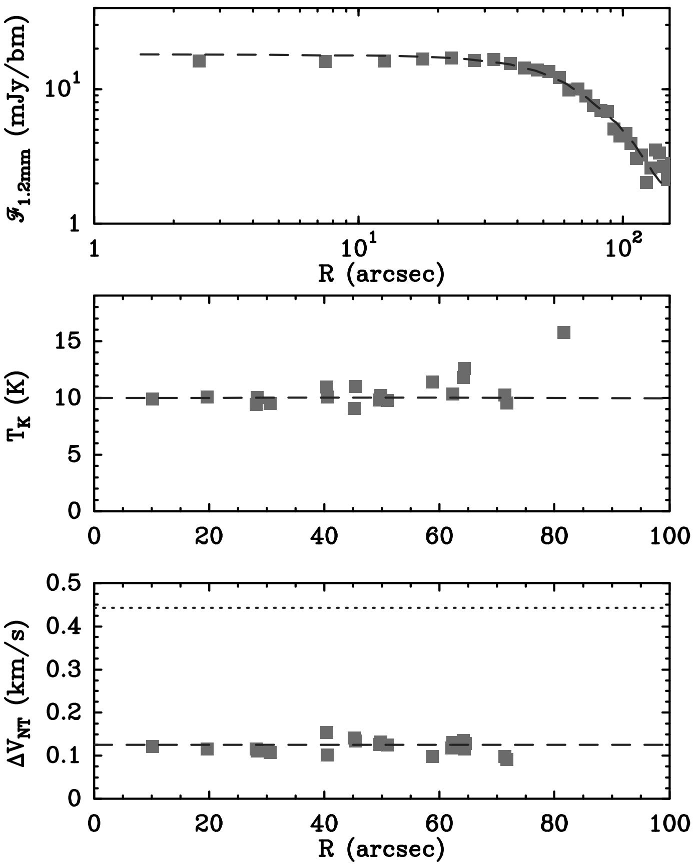

Figure 3. Determination of the physical parameters of L1498. Top: radial profile of 1.2mm continuum emission from the map of Fig. 2 (squares) and prediction from the best fit density determination (dashed lines). Middle: NH_3-derived gas kinetic temperature estimate (squares) and constant 10 K fit (dashed lines). Bottom: non thermal linewidth component derived from $NH_3(1,1)$ spectra (squares) and constant component with FWHM = 0.125 km/s (dashed lines). The dotted line indicates the expected value for a sonic component.

constant turbulent component of less than 1/3 the speed of sound. Such a low level of turbulence seems already problematic for current turbulent models of star formation.

3.2. *Chemical structure of L1498 and L1517B*

Once the physical structure of each core has been determined, the only free parameter left to fit the observed emission of a given species is the radial distribution of its abundance. To convert this distribution into a predicted line intensity, we use a Monte Carlo radiative transfer code that assumes spherical symmetry (Bernes 1979). For each observed transition, we require that the model fits both the radial distribution of integrated intensity (derived by averaging azimuthally the data) and the line spectrum observed toward the core center. When possible, we use the thin emission of a rare isotopomer (like $C^{18}O$ and $C^{34}S$) to determine the abundance of the major species (like CO and CS). As for most molecules we have observed two or more transitions, their abundance profile is over-determined by the data.

In a meeting like this one is important to emphasize that the analysis presented here can only be carried out if certain molecular parameters have been previously determined.

Among these parameters, the collision rates are critical because they regulate the excitation of the levels and therefore the relation between model abundance and predicted intensity. In fact, the availability of collision rates with H_2 or He was a main criterion for selecting the species observed in this survey. Another important molecular parameter needed to fit the narrow lines observed in L1498 and L1517B is the frequency of each transition. For our modelling, accuracies of 10 kHz are required, and although this level is now easily achievable in laboratory work, not all important molecular transitions have yet been measured with this detail; accurate laboratory frequencies of molecular ions are in particular absent. For our work, we have used the most recent frequency determinations from the CDMS, Gottlieb and collaborators, Dore and collaborators, and the JPL catalog.

To illustrate the process of deriving abundance profiles from the data, we present in Fig. 4 (top) a sample of integrated intensity maps for the L1498 core. The three panels in the left column show centrally concentrated distributions corresponding to the 1.2mm continuum, N_2H^+(1–0), and NH_3(1,1). The rest of the maps, on the other hand, show ring-like distributions with a relative minimum at the dust peak. These ring-like distributions are very fragmented and slightly different for each molecule, although there are systematic features, like a brighter peak to the southeast.

When we convert the above maps into radial profiles of integrated intensity and attempt to fit them with different abundance profiles, we obtain the results shown in the bottom part of Fig. 4. For each molecule, this figure shows two model predictions: a constant abundance model chosen to fit the emission in the outer core (dashed lines) and a best-fit model (solid lines). As the figure shows, the N_2H^+ emission is fit reasonably well by the constant abundance model, while the observed NH_3 emission is more centrally concentrated than predicted by a constant abundance model. This species, therefore, requires a significant enhancement of abundance toward the core center.

In agreement with the expectation from the ring-shaped maps, the rest of the molecules cannot be fit with a constant abundance model, as these models clearly overestimate the central intensity by a factor of 2 or more when forced to fit the outer core emission. Only using a sharp central abundance drop can both the outer and inner emission be simultaneously fit. For this reason, we have chosen for our best fit models simple step functions with close to zero abundance toward the center. From the quality of the fit, we conclude that the data are consistent with a (close to) total absence of certain molecules at the core center.

Although not shown here for lack of space, the abundance results for L1517B are very similar to those for L1498 (a full account of the analysis will be presented in Tafalla et al. 2005, in preparation). The outer abundances for both cores are in fact rather close, and for most species they agree within a factor of 2; this suggests that both objects have contracted from gas having similar chemical compositions. The size of the central hole, on the other hand, is different in the two cores. L1517B presents significantly smaller central molecular holes (about 50% smaller than L1498), which may be related to the more concentrated gas distribution found in this core.

3.3. *Consequences for dense core studies*

L1498 and L1517B seem in every aspect typical pre-stellar cores. More restricted studies of other systems by different authors, as those presented in this meeting by the posters of Butner et al., Buckle et al., Friesen et al., Zinchenko et al., show patterns of molecular abundance very similar to those found in L1498 and L1517B; it seems therefore natural to assume that the abundance profiles of L1498 and L1517B are representative of the pre-stellar core population as a whole (see also below for exceptions). Thus, despite

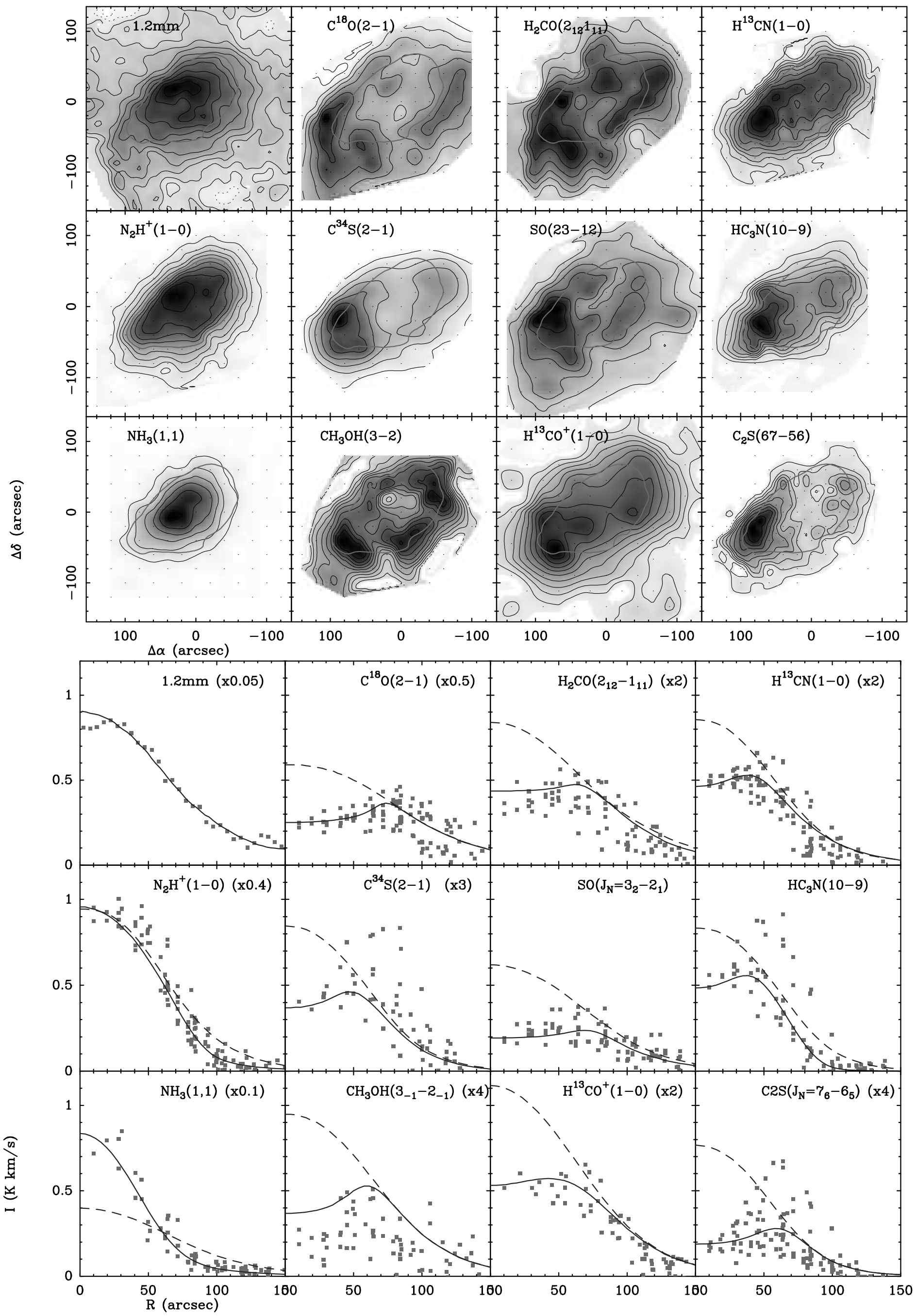

Figure 4. Partial results of the molecular survey toward L1498. Top: maps of 1.2mm continuum and molecular lines for a sample of transitions. The three panels in the leftmost column contain centrally concentrated emission maps, while the rest of the panels show ring-shaped distributions. Bottom: Radial profiles of emission derived from the maps in the top (squares) together with the emission predictions from two Monte Carlo models. The dashed lines are the predictions from constant abundance models set to fit the outer core emission, while the solid lines are predictions from the best-fit models.

their expected simplicity, pre-stellar cores must have a strongly differentiated chemical composition.

If chemical inhomogeneities are part of the initial conditions of star formation, they need to be considered seriously when sampling star-forming gas with molecular tracers. The bottom panels in Fig. 4, in particular, show that many molecular maps of a core may reflect more its chemical composition than its physical structure, and illustrate the danger in attributing emission peaks of even thin lines like $C^{34}S(2–1)$ to real core substructure. A main lesson from this analysis is therefore that one needs to be careful when choosing dense gas tracers, and that N_2H^+ and NH_3 are some of the best choices we have. These species, together with their isotopomers and the H_2D^+ ion recently detected by Caselli et al. (2003) in the pre-stellar core L1544, are probably all the molecular tracers left to study the conditions in the inner core (even N_2H^+ may deplete at high densities, see Bergin et al. 2002 and Pagani et al. 2005). Posters in this meeting by Crapsi et al. and Vastel et al. show the use of these more reliable tracers to study the central conditions of pre-stellar cores.

The modelling of pre-stellar core chemistry is the subject of several contributions in this meeting (talks by Shematovich and Roberts, and posters by Aikawa et al., Rawlings, Lee et al., Walmsley et al.), so I refer to them for further details on this topic. The only point worth emphasizing here is that the unique behaviour of species like N_2H^+ and NH_3 strongly suggests that their survival in the gas phase results from a low binding energy of N_2, as initially suggested by Bergin & Langer (1997) and Charnley (1997). However, similar binding energies for N_2 and CO have been recently measured by Öberg et al. (2005), a result that has been used to claim that other mechanisms, like a low sticking coefficient for molecular or atomic N, may be needed to explain the behaviour of N_2H^+ and NH_3 (Flower et al. 2005). Further work in this topic is clearly needed if we are to understand and use to our advantage the peculiar chemistry of these two important dense gas tracers.

4. Searching for young pre-stellar cores

If we observe pre-stellar cores selected from NH_3 surveys (like those from Myers and collaborators), we find that molecular depletion is the norm without exception. This systematic trend suggests that NH_3-selected cores are significantly advanced in their process of gas contraction from the ambient cloud, and that there must exist a population of younger cores that are their precursors. Identifying such a population of cores is interesting not only because of their chemical properties, but because its members should constitute a missing link between cloud and core conditions, and they will therefore provide useful clues on the (mysterious) physical process that drives core condensation out of ambient material.

To search for young pre-stellar cores, we can take advantage of their expected chemical properties. One of them is a lower degree of CO freeze out at the center, which should make a young pre-stellar core appear centrally concentrated in a $C^{18}O$ map. Another expected property is a low abundance of late-time species like N_2H^+ and NH_3, which will translate into weak emission in any line of these tracers. To relate these properties, we define the intensity ratio

$$R = \frac{I[\mathrm{C}^{18}\mathrm{O}(1-0)]}{I[\mathrm{N}_2\mathrm{H}^+(1-0)]},$$

where the intensities are evaluated at the core center. This ratio is an easily measurable quantity, as both lines lie in the 3mm wavelength band and can therefore be observed

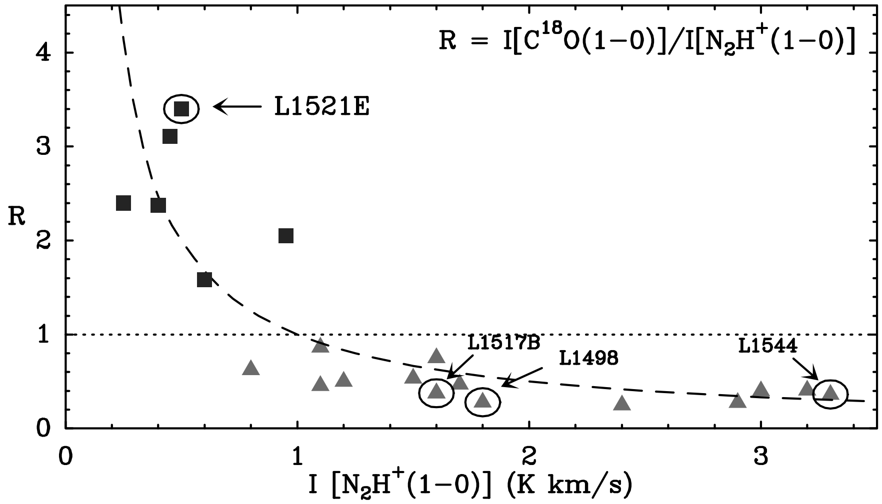

Figure 5. R (=I[$C^{18}O$(1-0)]/I[N_2H^+(1-0)]) as function of I[N_2H^+(1-0)] for two samples of cores. The triangles are "classical" starless cores selected for their easily detectable NH_3 emission, while the squares are starless cores selected for their weak NH_3 emission. The dotted horizontal line marks the expected approximate boundary between cores with and without $C^{18}O$ freeze out, and the dashed line is the prediction from a toy model of core chemical evolution. Note how L1521E stands out among the young core candidates (R> 1).

with similar angular resolution. Young cores are expected to have relatively large central $C^{18}O$(1–0) emission together with weak N_2H^+(1–0) lines, so they are expected to have relatively large values of the R parameter. Conversely, old cores are expected to have relatively weak central $C^{18}O$(1–0) emission and strong N_2H^+(1–0) lines, so they should be characterized by relatively low values of R. The approximate boundary between these two behaviours can be calculated using the ratio predicted by our Monte Carlo model for cores like L1498 and L1517B assuming constant abundances for the two species. In this way, we find the expected separation between young and old cores near the value $R = 1$.

As mentioned before, searches for young cores using NH_3-selected candidates seem doomed to fail, and this is illustrated by the triangles in Fig. 5, which correspond to a survey of that type of objects carried out with the FCRAO telescope. In this figure, all selected objects lie below the $R = 1$ line, including (not surprisingly) L1498 and L1517B studied before. The objects from this survey probably span a range of ages, as suggested by the range of N_2H^+(1–0) intensities that starts near 1 and ends past 3 with evolved cores like L1544 (e.g., Crapsi et al. 2005). However, they seem to be missing the youngest cores.

To identify candidates to young starless cores we need to include cores having weak NH_3 emission, and this has been done selecting sources from the survey of Suzuki et al. (1992) and from a survey of the L1521 filament in Taurus using the FCRAO telescope. These cores finally fill the region in the plot expected for young cores, as they have low N_2H^+(1–0) intensities together with large R values. Among these objects, L1521E has the largest R ratio (=3.4), and therefore appears as the best candidate for a young starless core. Previous suggestions of this core being extremely young have been made by Suzuki et al. (1992) and Hirota et al. (2002).

Given the unusual characteristics of L1521E, we have carried out a molecular survey of this core in a similar manner as we have studied L1498 and L1517B. From a preliminary analysis of these data, we conclude that it has no significant CO or CS central

depletion (Tafalla & Santiago 2004), and that its N_2H^+ and NH_3 abundance is 8 times lower and 20 times lower than L1498 and L1517B. These characteristics truly classify L1521E as a chemically young pre-stellar core, and therefore suggest that this object has contracted from the ambient cloud to its observed state rather recently. Surprisingly, however, L1521E has a central density of 10^5 cm^{-3}, which is very similar to that found in L1498 and L1517B. This high density contradicts the expectation that a young core should be less dense, and suggests that L1521E may have contracted faster than the others (also Aikawa et al. 2005). Clearly more work is needed to clarify the origin of this group of starless cores, and recent studies of similar systems are encouraging (Hirota et al. 2004, Morata et al. 2005). The poster by Hirota and Yamamoto in this meeting provides recent results on this topic.

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References

Adams, F.C. & Myers, P.C. 2001, *ApJ* 553, 744
Aikawa, Y., Herbst, E., Roberts, H. & Caselli, P. 2005, *ApJ* 620, 330
Alves, J., Lada, C.J. & Lada, E.A. 2001, *Nature* 409, 159
Benson, P.J., & Myers, P.C. 1989, *ApJS* 71, 89
Bergin, E.A. & Langer, W.D. 1997, *ApJ* 486, 316
Bergin, E.A., Alves, J., Huard, T. & Lada, C.J. 2002, *ApJ* 570, L101
Bernes, C. 1979, *A&A* 73, 67
Caselli, P., Walmsley, C.M., Tafalla, M., Dore, L. & Myers, P.C. 1999, *ApJ* 523, L165
Caselli, P., van der Tak, F.F.S., Ceccarelli, C. & Bacmann, A. 2003, *A&A* 403, L37
Charnley, S.B. 1997, *MNRAS* 291, 455
Crapsi, A., Caselli, P., Walmsley, C.M., Myers, P.C., Tafalla, M., Lee, C.W. & Bourke, T.L. 2005, *ApJ* 619, 379
Evans, N.J., II, Rawlings, J.M.C., Shirley, Y.L. & Mundy, L.G. 2001 *ApJ* 557, 193
Flower, D.R., Pineau Des Forêts, G. & Walmsley, C.M.2005 *A&A* 436, 933
Hirota, T., Ito, T. & Yamamoto, S. 2002 *ApJ* 565, 359
Hirota, T., Maezawa, H. & Yamamoto, S. 2004 *ApJ* 617, 399
Kramer, C., Alves, J., Lada, C.J., Lada, E.A., Sievers, A., Ungerechts & Walmsley, C.M. 1999, *A&A* 342, 257
Kuiper, T.B.H., Langer, W.D. & Velusamy, T. 1996, *ApJ* 468, 761
Mac Low, M.-M. & Klessen, R.S. 2004, *Rev. Mod. Phys* 76, 125
Morata, O., Girart, J.M. & Estalella, R. 2005 *A&A* 435, 113
Mouschovias, T.C. & Ciolek, G.E. 1999, in C.J. Lada and N.D. Kylafis (eds.), *The Origin of Stars and Planetary Systems (Dordrecht: Kluwer)* p.305
Öberg, K.I., van Broekhuizen, F., Fraser, H.J., Bisschop, S.E., van Dishoeck, E.F. & Schlemmer, S. 2005, *A&A* 621, L33
Pagani, L., Pardo, J.-R., Apponi, A.J., Bacmann, A. & Cabrit, S. 2005, *A&A* 429, 181
Shu, F.H., Adams, F.C. & Lizano S. 1987, *ARAA* 25, 23
Suzuki, H., Yamamoto, S., Ohishi, M., Kaifu, N., Ishikawa, S.-I., Hirahara, Y. & Takano, S. 1992, *ApJ* 392, 551
Tafalla, M., Myers, P.C., Caselli, P. & Walmsley, C.M. 2004, *A&A* 416, 191
Tafalla, M. & Santiago, J. 2004, *A&A* 414, L53
Ward-Thompson, D., Motte, F. & André, P. 1999, *A&A* 305, 143

Watson, W.D. & Salpeter, E.E. 1972, *ApJ* 175, 659
Willacy, K., Langer, W.D. & Velusamy, T. 1998, *ApJ* 507, L171
Zhou, S., Wu, Y., Evans, N.J.II, Fuller, G.A. & Myers, P.C. 1989, *ApJ* 346, 168